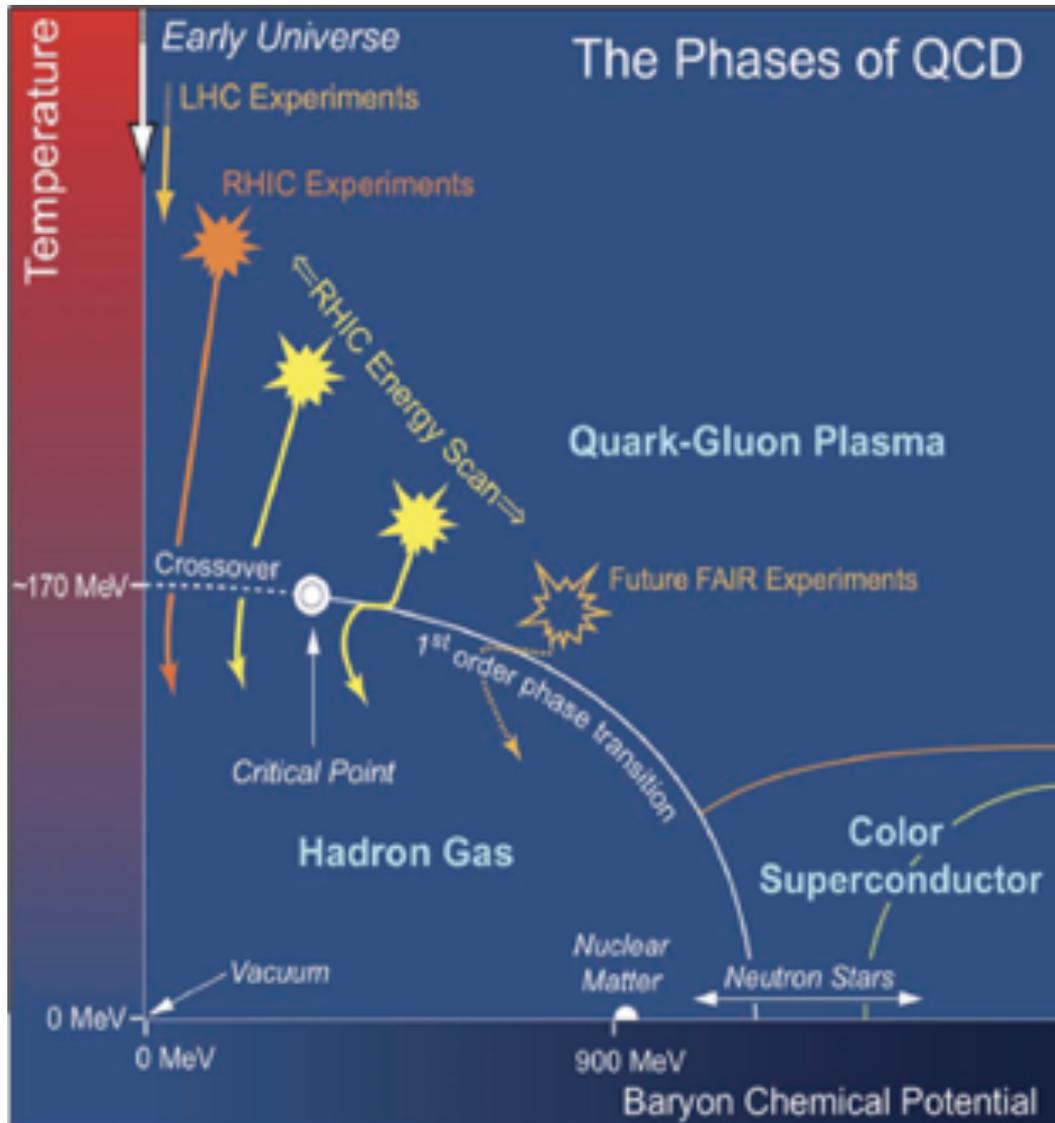


Energy Dependence of Moments of Net-Proton, Net-Kaon and Net-Charge Multiplicity Distributions at STAR

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- Introduction
- Analysis Techniques and Details
- Results for Net-Proton, Net-Charge and Net-Kaon
- Summary



- Crossover at $\mu_B=0$.
- First order phase transition expected at large μ_B .
- QCD Critical Point: The end point of first order phase transition boundary.
- Does CP(Critical Point) exist? Where is it?

STAR Note 0598

- Sensitivity to correlation length (ξ) and probe non-gaussian fluctuations near the Critical Point.

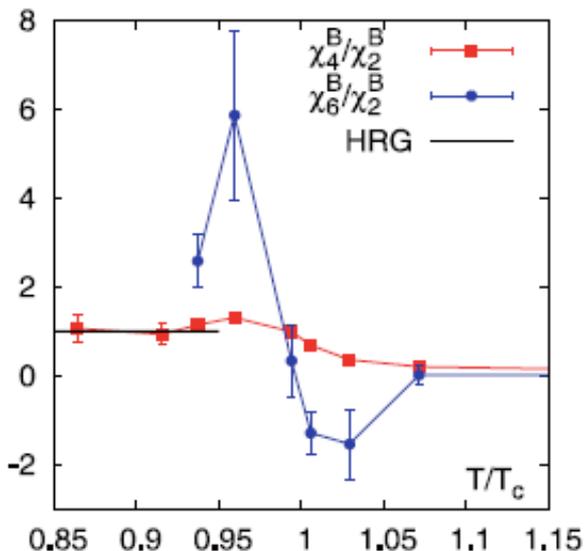
$$\langle (\delta N)^2 \rangle \sim \xi^2, \langle (\delta N)^3 \rangle \sim \xi^{4.5}, \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \sim \xi^7$$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).

M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).

M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

- Direct connection to the susceptibility of the system.



$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial (\mu_q)^n}, q = B, Q, S$$

S. Ejiri et al, Phys.Lett. B 633 (2006) 275.

Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694.

F. Karsch and K. Redlich, PLB 695, 136 (2011).

S. Gupta, et al., Science, 332, 1525(2012).

A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903

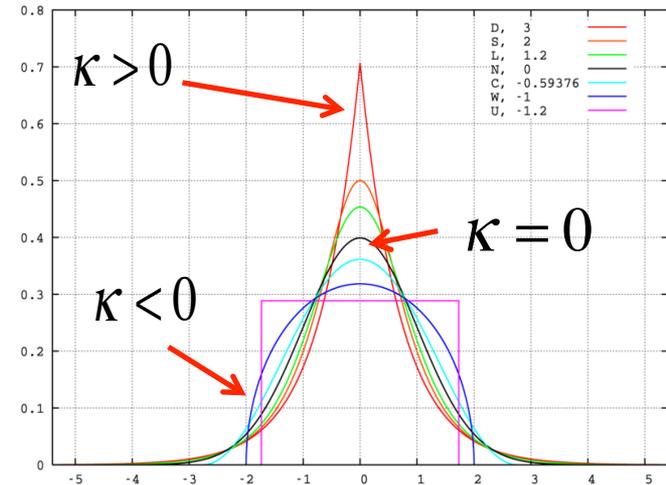
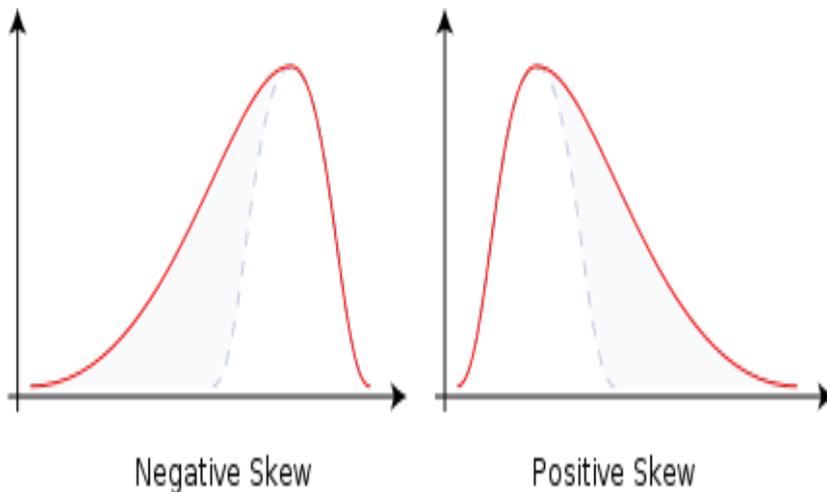
“Shape” of the fluctuations can be measured: non-Gaussian moments (cumulants):

$$C_{1,x} = \langle x \rangle, C_{2,x} = \langle (\delta x)^2 \rangle,$$

$$C_{3,x} = \langle (\delta x)^3 \rangle, C_{4,x} = \langle (\delta x)^4 \rangle - 3 \langle (\delta x)^2 \rangle^2$$

$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$$

$$\kappa = \frac{C_{4,N}}{(C_{2,N})^2} = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$$



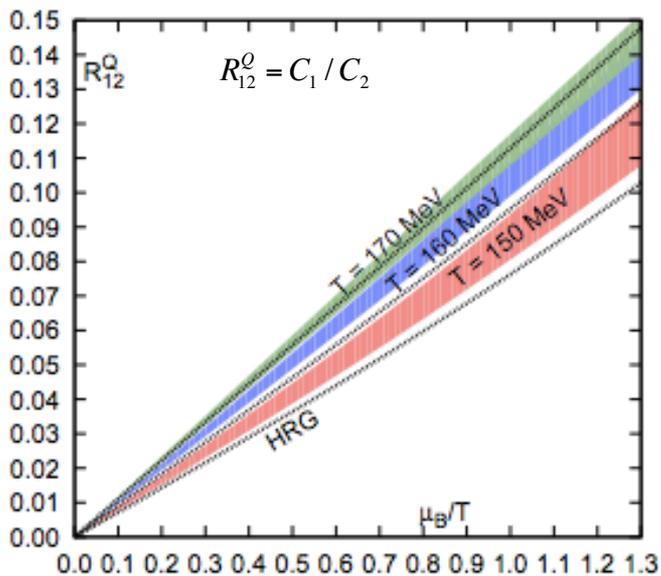
➤ Cumulant Ratios (Cancel V dependence)

$$\kappa \sigma^2 = \frac{C_{4,q}}{C_{2,q}}$$

$$S \sigma = \frac{C_{3,q}}{C_{2,q}},$$

(q=B, Q, S)

- Experimentally, we measured the net-particle multiplicity fluctuations: net-charge, net-proton (proxy for net-baryon), net-kaon (proxy for net-strangeness). The main observable is volume independent cumulant ratios.



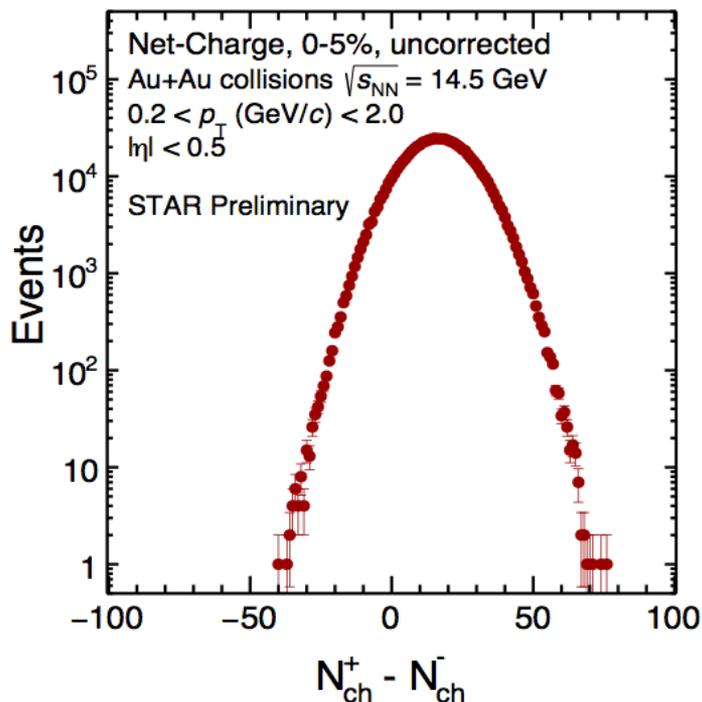
HotQCD, PRL109, 192302 (2012)
 WB Group, PRL111, 062005 (2013)

$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

$$\frac{\chi_3^i}{\chi_2^i} = (S\sigma)^i = \frac{c_3^i}{c_2^i}$$

$$\frac{\chi_4^i}{\chi_2^i} = (\kappa\sigma^2)^i = \frac{c_4^i}{c_2^i}$$

$i = B, Q, S$



Theory



Experiment

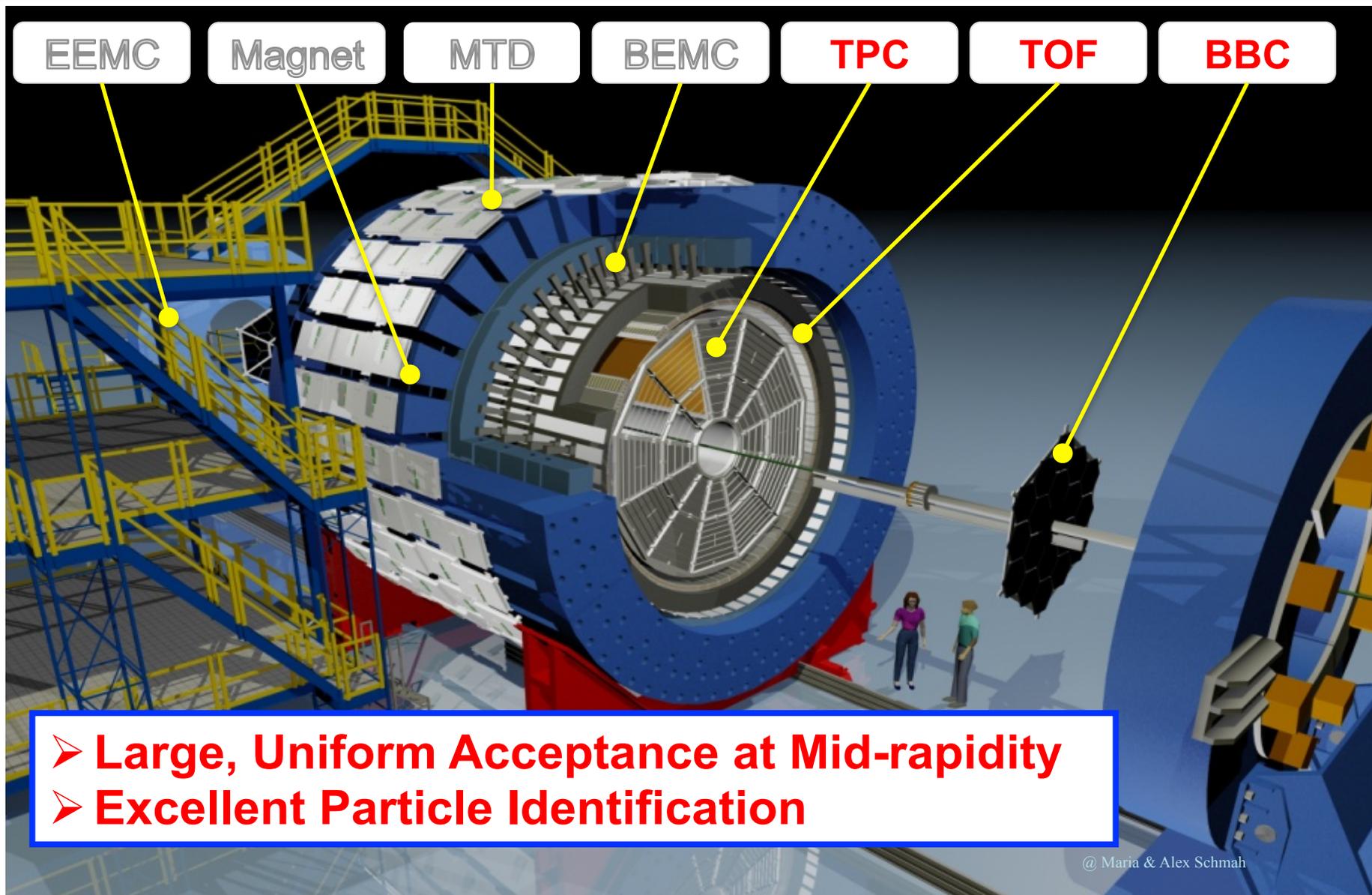
- In the first phase of the Beam Energy Scan (BES) program at RHIC, eight beam energies have already been analyzed from $\sqrt{s_{NN}}=7.7\text{GeV}$ to 200GeV .

\sqrt{s} (GeV)	Statistics (Millions)	Year	μ_B (MeV)	T (MeV)	μ_B / T
7.7	~4	2010	420	140	3.020
11.5	~12	2010	315	152	2.084
14.5	~20	2014	266	156	1.705
19.6	~36	2011	205	160	1.287
27	~70	2011	155	163	0.961
39	~130	2010	115	164	0.684
62.4	~67	2010	70	165	0.439
200	~350	2010	20	166	0.142

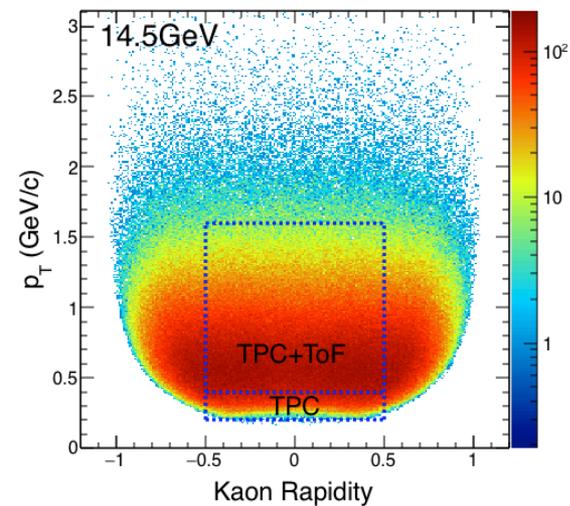
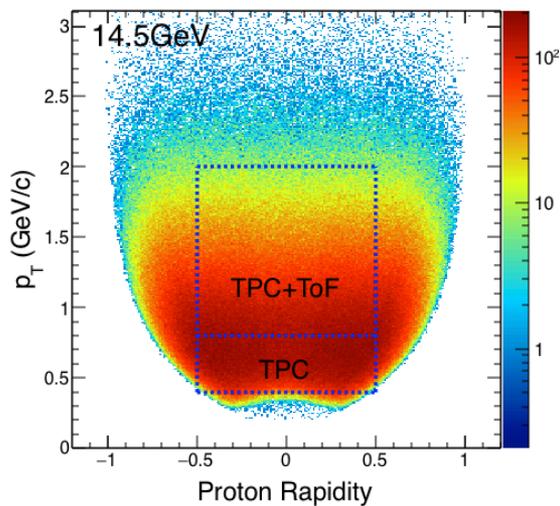
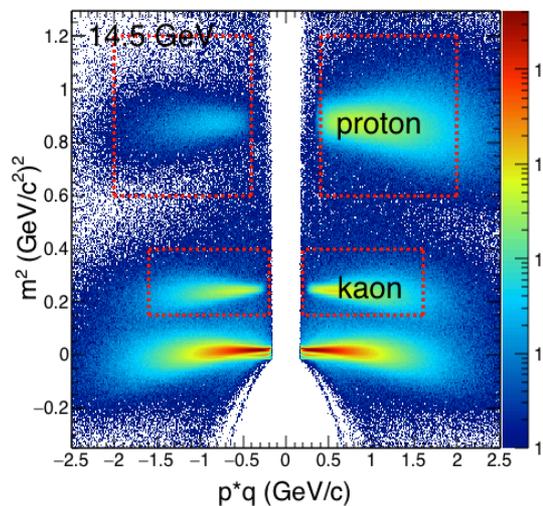
μ_B, T : J. Cleymans et al., PRC 73, 034905 (2006)

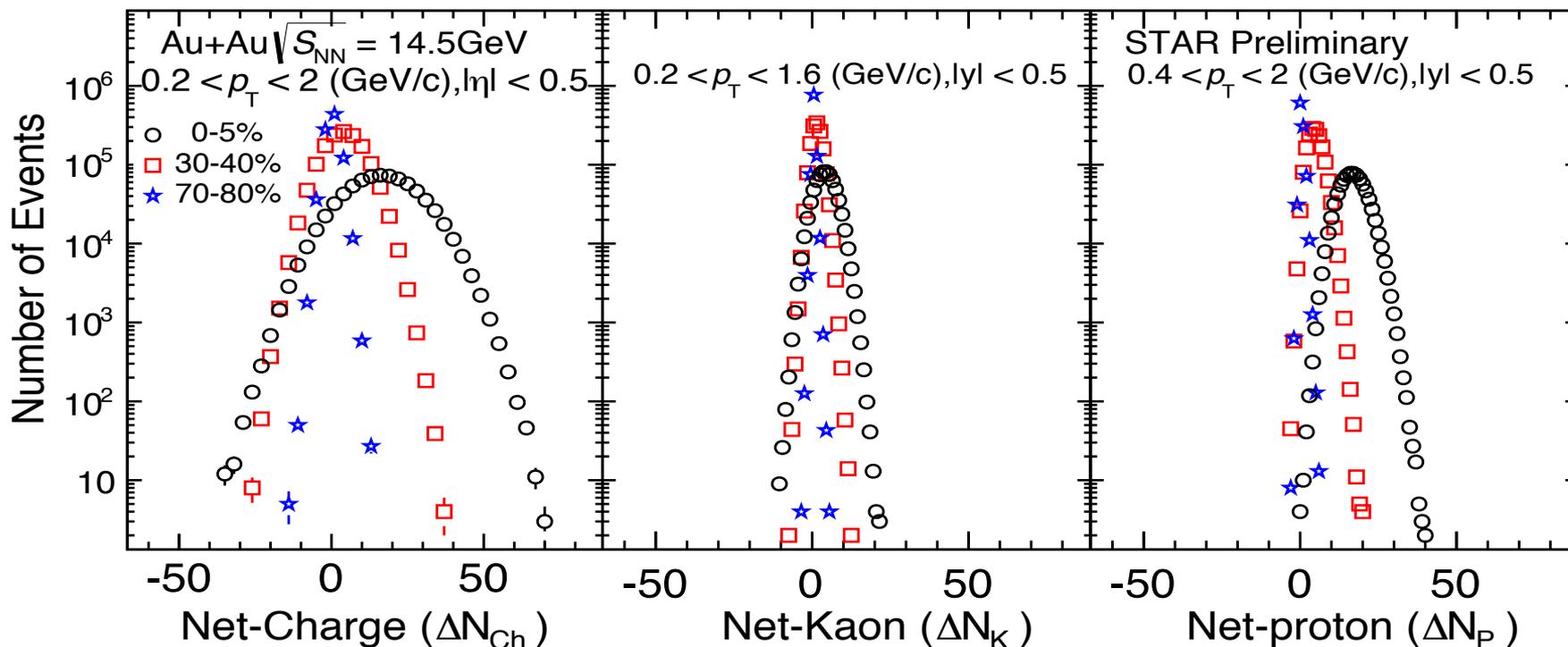
Study QCD Phase Structure

- Onset of sQGP
- Phase boundary and **critical point.**



	Net-Charge	Net-Proton	Net-Kaon
Kinematic cuts	$0.2 < p_T \text{ (GeV/c)} < 2.0$ $ \eta < 0.5$	$0.4 < p_T \text{ (GeV/c)} < 2.0$ $ y < 0.5$	$0.2 < p_T \text{ (GeV/c)} < 1.6$ $ y < 0.5$
Particle Identification	Reject protons from spallation for $p_T < 0.4 \text{ GeV/c}$	$0.4 < p_T \text{ (GeV/c)} < 0.8 \rightarrow \text{TPC}$ $0.8 < p_T \text{ (GeV/c)} < 2.0 \rightarrow \text{TPC+TOF}$	$0.2 < p_T \text{ (GeV/c)} < 0.4 \rightarrow \text{TPC}$ $0.4 < p_T \text{ (GeV/c)} < 1.6 \rightarrow \text{TPC+TOF}$
Centrality definition, <i>→ to avoid auto-correlations</i>	Uncorrected charged primary particles multiplicity distribution	Uncorrected charged primary particles multiplicity distribution, without (anti-)protons	Uncorrected charged primary particles multiplicity distribution, without (anti-)kaons
	$0.5 < \eta < 1.0$	$ \eta < 1.0$	$ \eta < 1.0$





Effects needed to be addressed to get final moments/cumulants:

1. Auto-correlation effects.
2. Effects of volume fluctuations.
3. Finite detector efficiency .

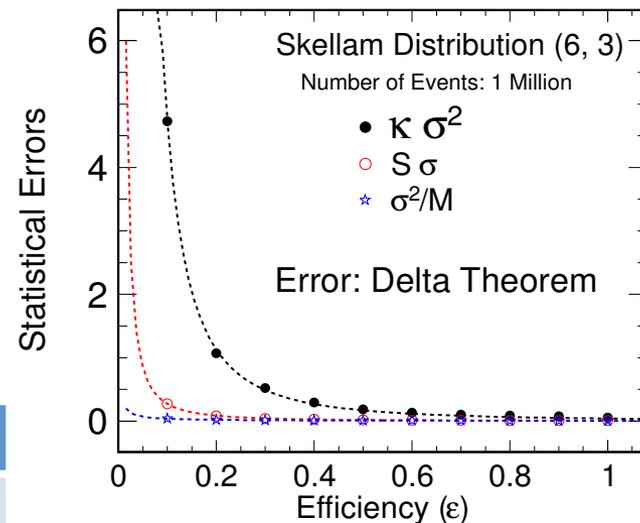
A. Bzdak and V. Koch, PRC86, 044904 (2012)
 X.Luo, et al. J. Phys. G40,105104(2013)
 X.Luo, Phys. Rev. C 91, 034907 (2015)
 A . Bzdak and V. Koch, PRC91, 027901 (2015)

- We can express the moments and cumulants in terms of the factorial moments, which can be easily efficiency corrected. X. Luo, PRC91, 034907 (2015); A. Bzdak and V. Koch, PRC91, 027901 (2015)
- Statistical Errors based on Delta Theorem. With same N events: $\text{error}(\text{net-charge}) > \text{error}(\text{net-kaon}) > \text{error}(\text{net-proton})$

Au+Au 14.5GeV	Net-Charge	Net-Proton	Net-Kaon
Typical Width(σ)	12.2	4.2	3.4
Average efficiency(ϵ)	65%	75%	38%
σ^2/ϵ^2	355	32	82

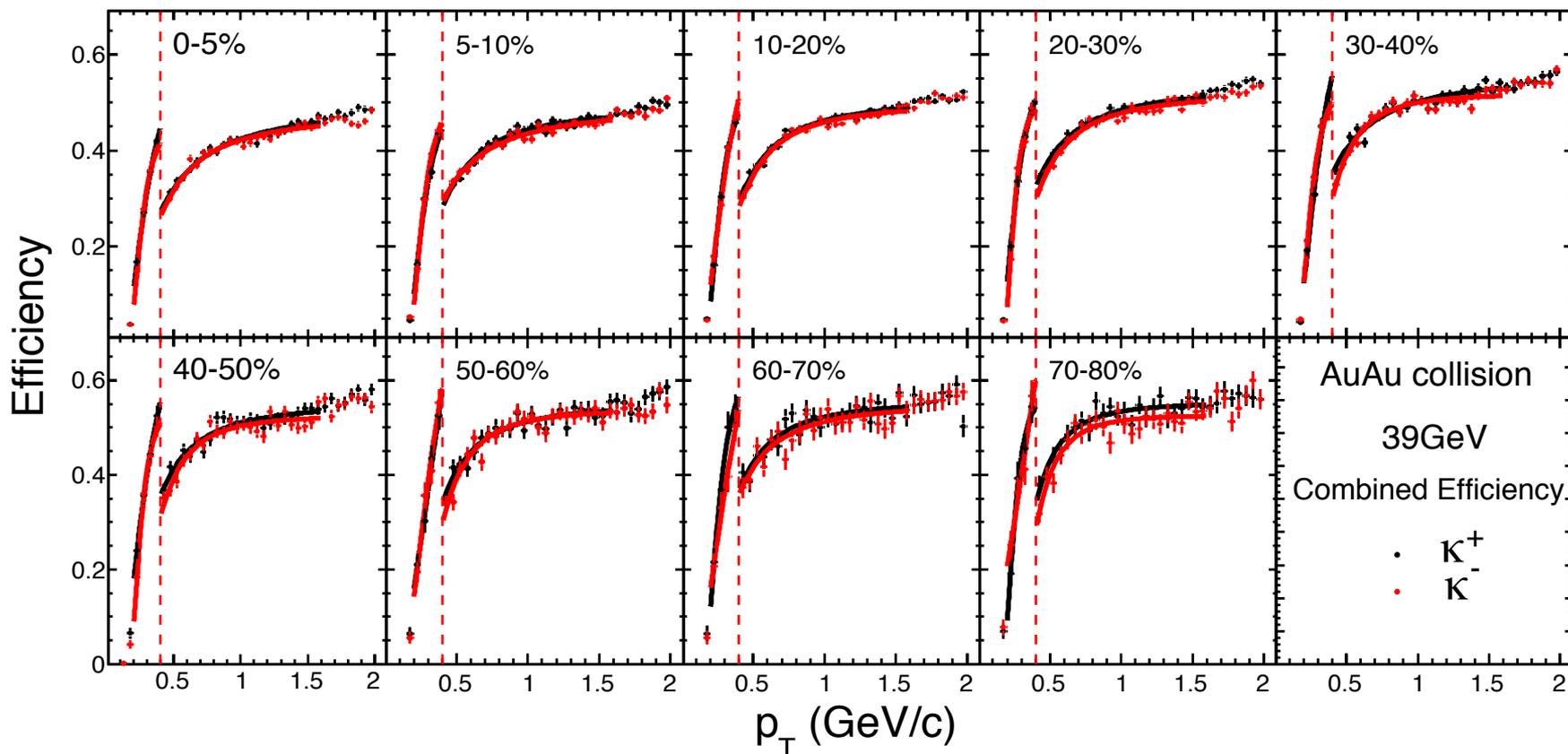
numbers here not used in actual analysis

- Systematic error estimation
 - Includes uncertainties on efficiency and efficiency fluctuations
 - PID and track cuts

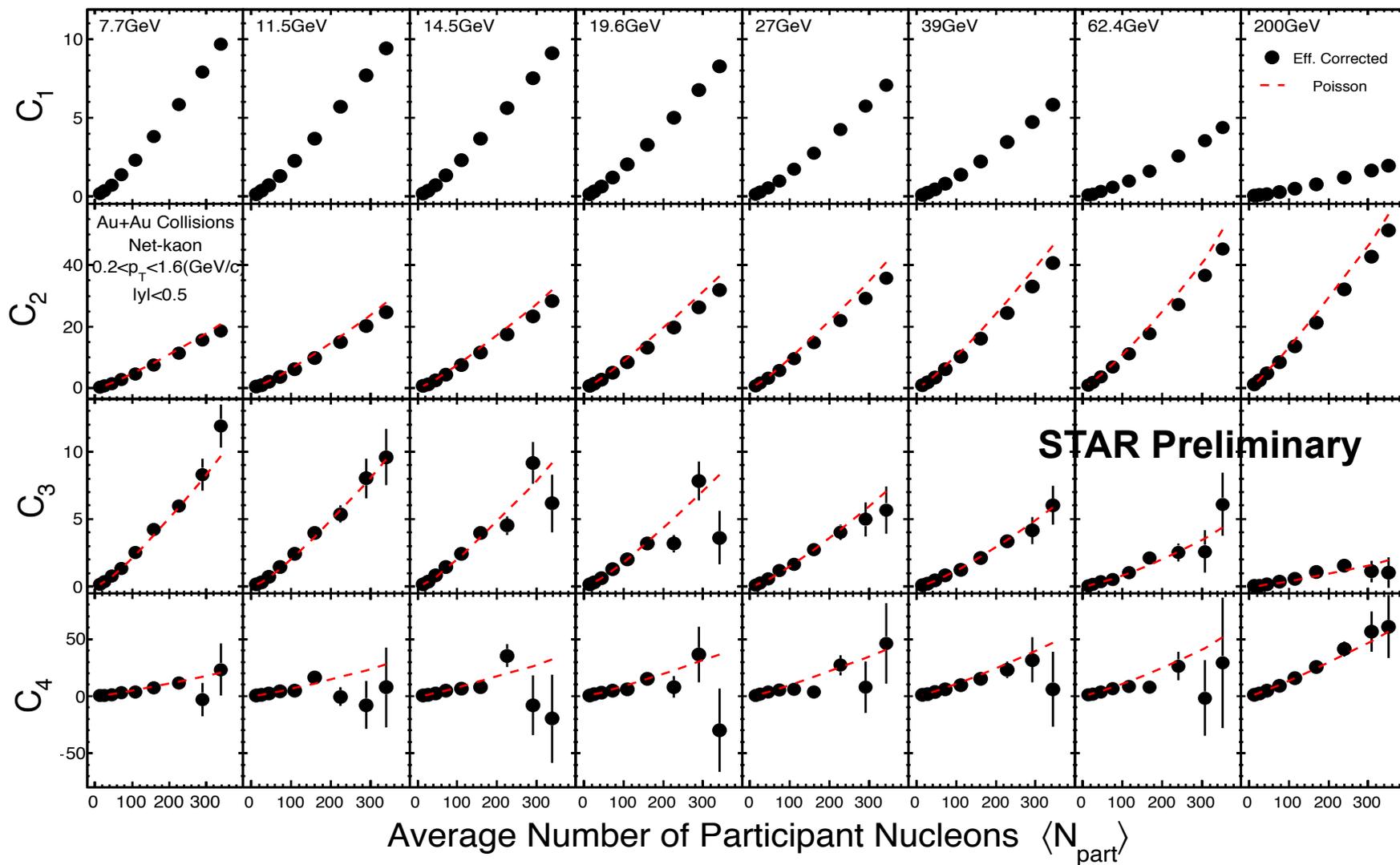


$$\text{error}(S\sigma) \propto \frac{\sigma}{\epsilon^{3/2}}$$

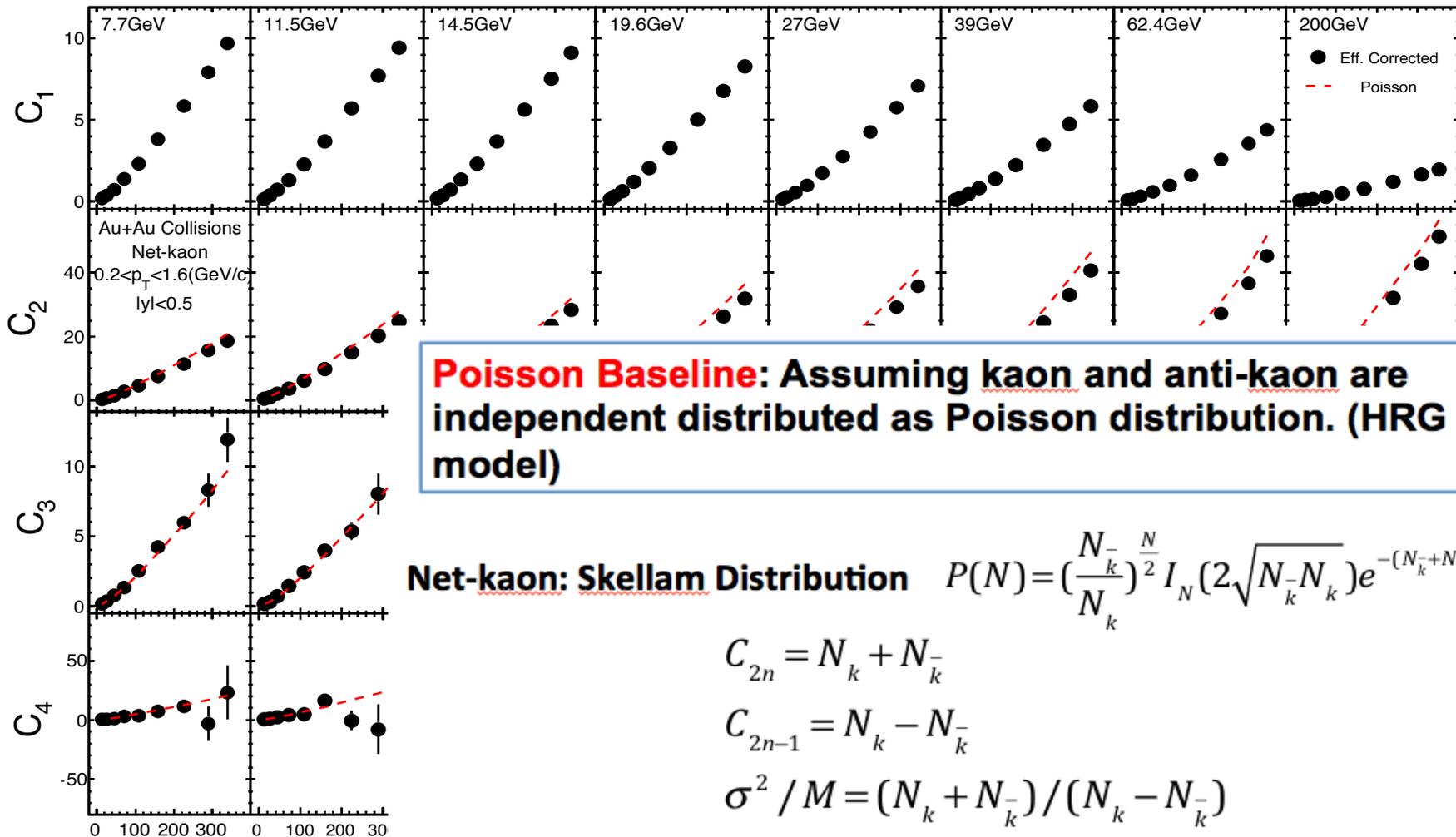
$$\text{error}(\kappa\sigma^2) \propto \frac{\sigma^2}{\epsilon^2}$$



- $0.2 < p_T < 0.4$ (GeV/c), TPC only
- $0.4 < p_T < 1.6$ (GeV/c), TPC+TOF
- Efficiency = Efficiency(Tracking) * Efficiency(TOF match)
- The input number is the p_T weighted average efficiency.



C_3 and C_4 generally consistent with Poisson expectation.



Net-kaon: Skellam Distribution

$$P(N) = \left(\frac{N_-}{N_k}\right)^{\frac{N}{2}} I_N(2\sqrt{N_- N_k}) e^{-(N_k + N_-)}$$

$$C_{2n} = N_k + N_-$$

$$C_{2n-1} = N_k - N_-$$

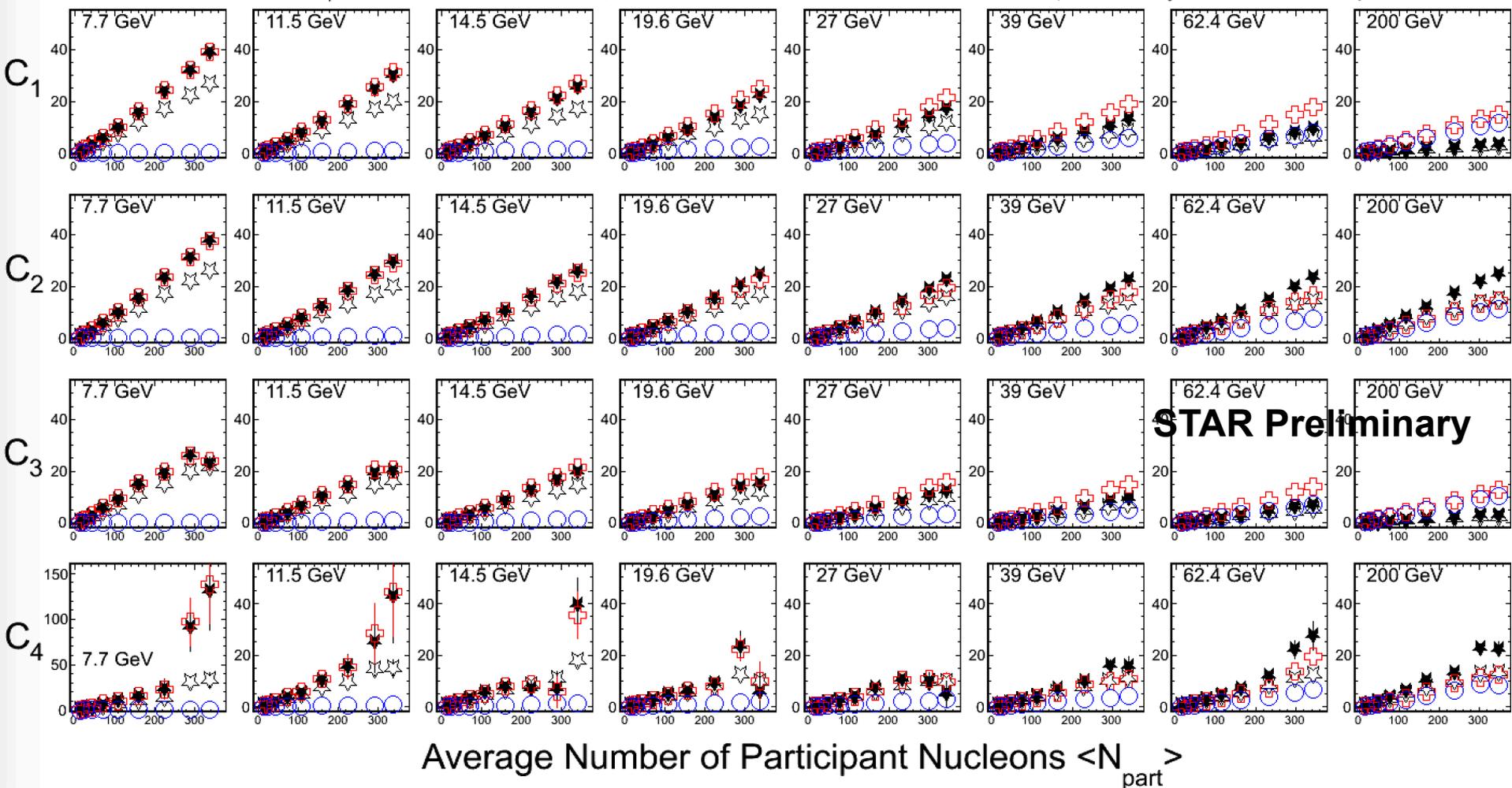
$$\sigma^2 / M = (N_k + N_-) / (N_k - N_-)$$

$$S\sigma = (N_k - N_-) / (N_k + N_-)$$

$$\kappa\sigma^2 = 1$$

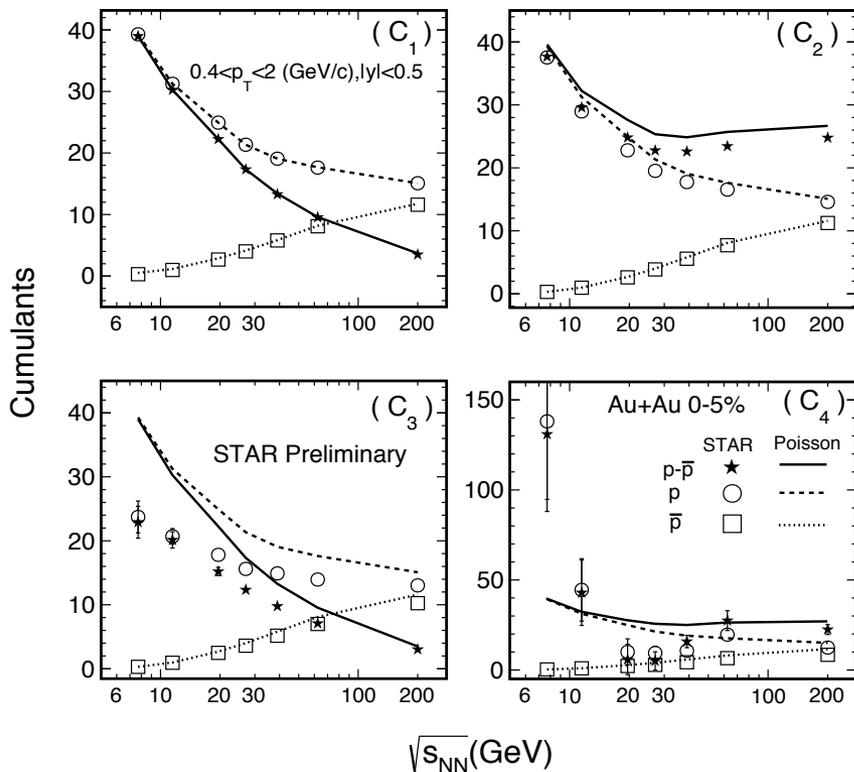
C_3 and C_4

Au+Au Collisions $0.4 < p_t < 2$ (GeV/c), $|y| < 0.5$
 ★ Net-proton + Proton ○ Anti-proton ☆ Efficiency Uncorrected Net-proton

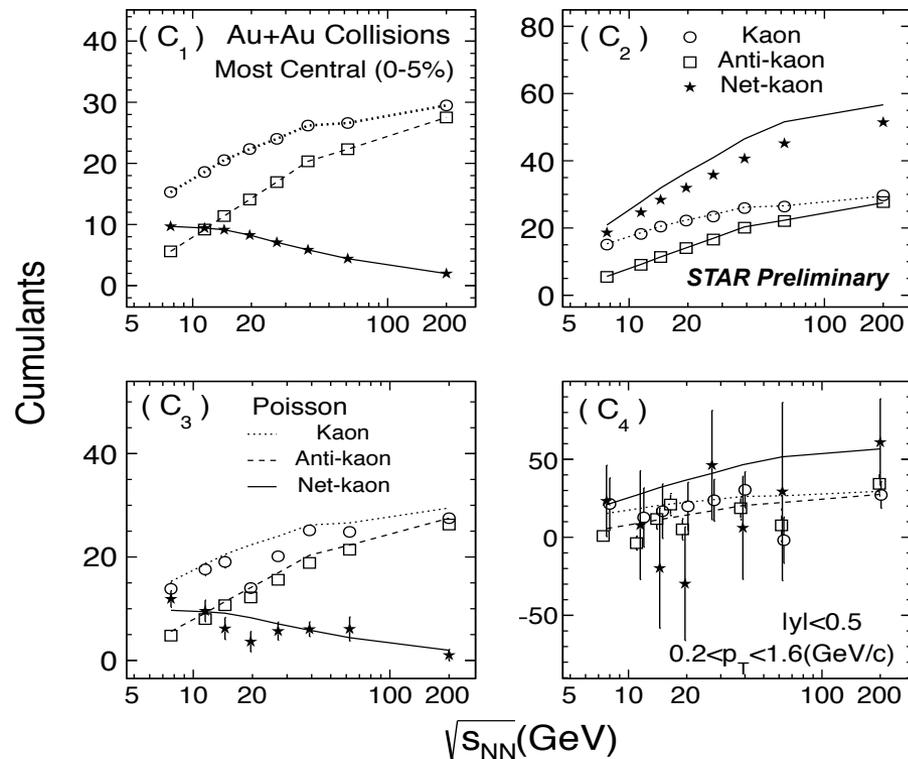


In general, cumulants are increasing with $\langle N_{part} \rangle$.

Cumulants vs. Poisson (Protons)

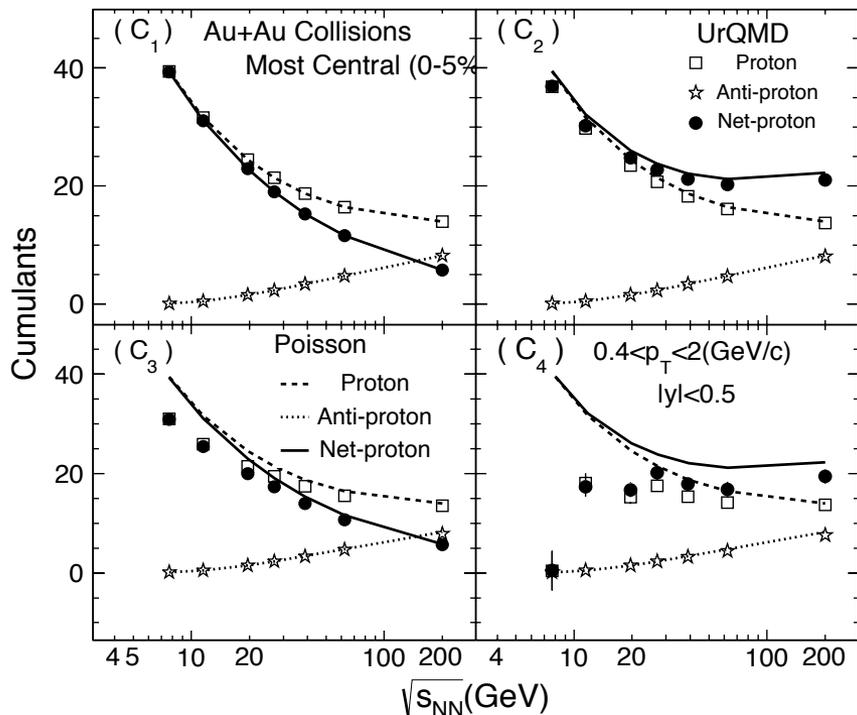


Cumulants vs. Poisson (Kaons)

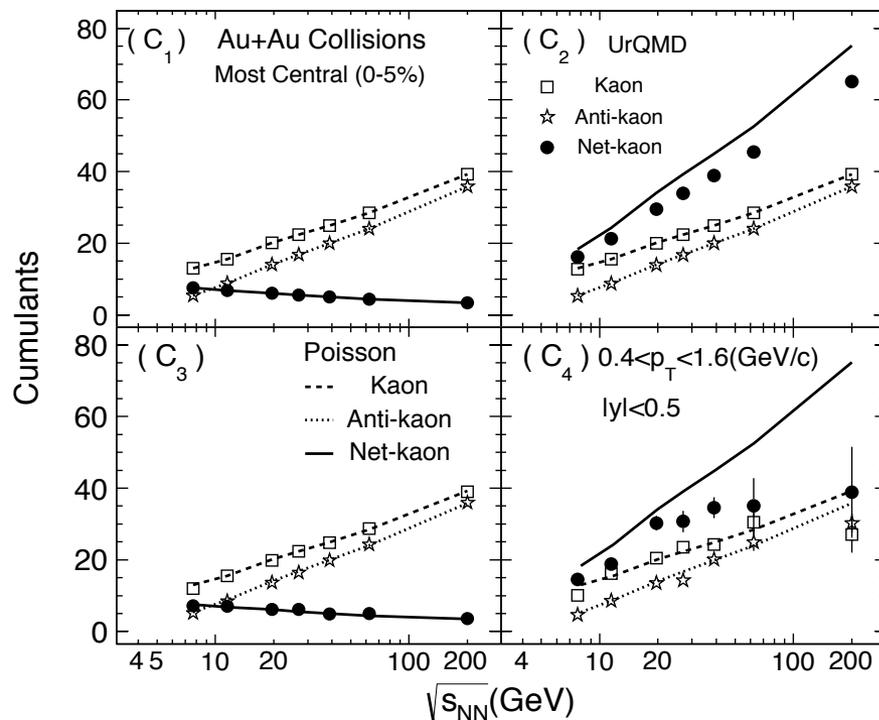


- The higher the order of cumulants, the larger deviations from Poisson expectations for net-proton and proton.
- In general, the cumulants for net-kaon, kaon and antikaon are consistent with Poisson baseline within uncertainties.

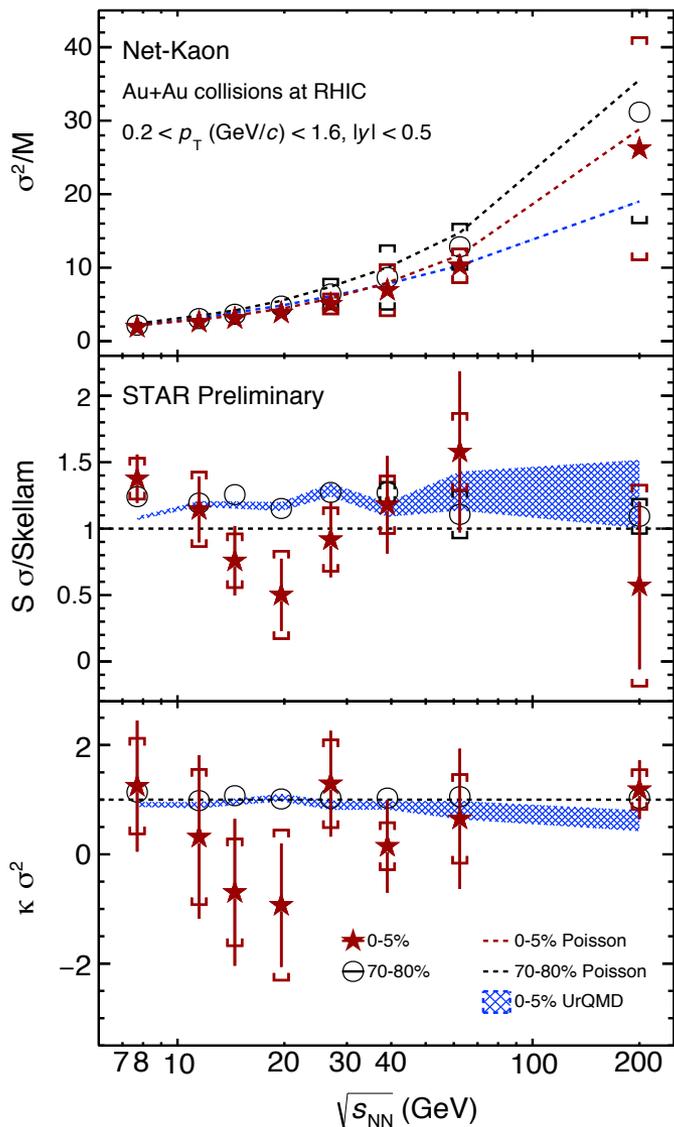
Cumulants vs. Poisson (Protons)



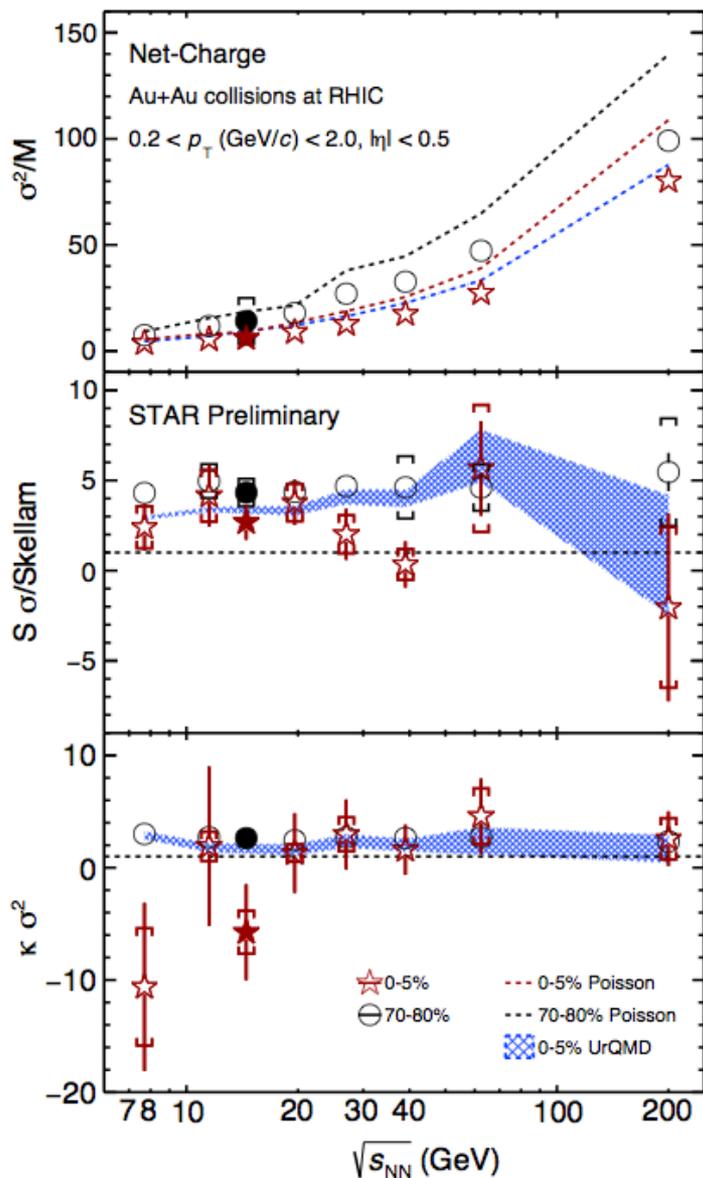
Cumulants vs. Poisson (Kaons)



- Deviations from Poisson expectations for net-proton and proton are observed at low energies due to the baryon stopping effect.
- In general, the cumulants for net-kaon, kaon and antikaon are consistent with Poisson baseline within uncertainties.



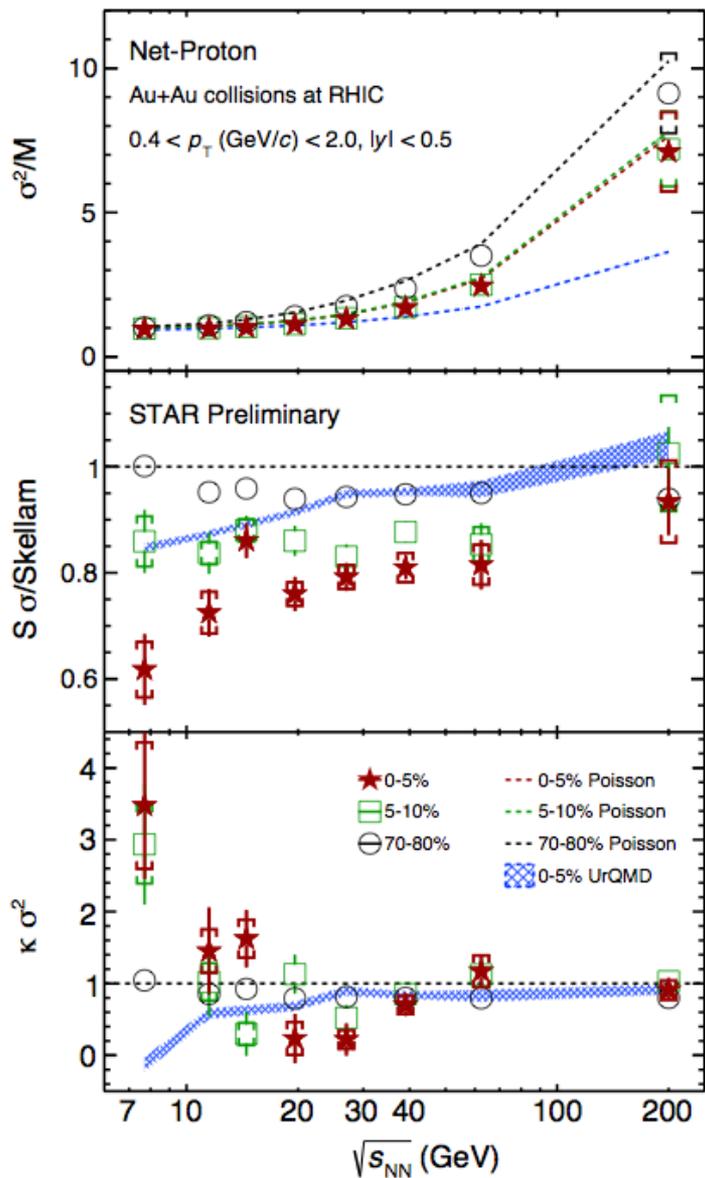
- The values of σ^2/M increase as the energy increases.
- The values of $S\sigma/Skellam$ are consistent with unity, within uncertainties.
- The values of $\kappa\sigma^2$ are consistent with unity within uncertainties.
- UrQMD (no Critical Point), shows no energy dependence.



- 14.5 GeV data-point added to the published data. Fits well into trends

Phys. Rev. Lett. 113, 092301 (2014)

- σ^2/M increases with increasing collision energy.
- $\kappa \sigma^2$ and $S \sigma/Skellam$ are consistent with unity within uncertainties.
- UrQMD (no Critical Point), shows no energy dependence.



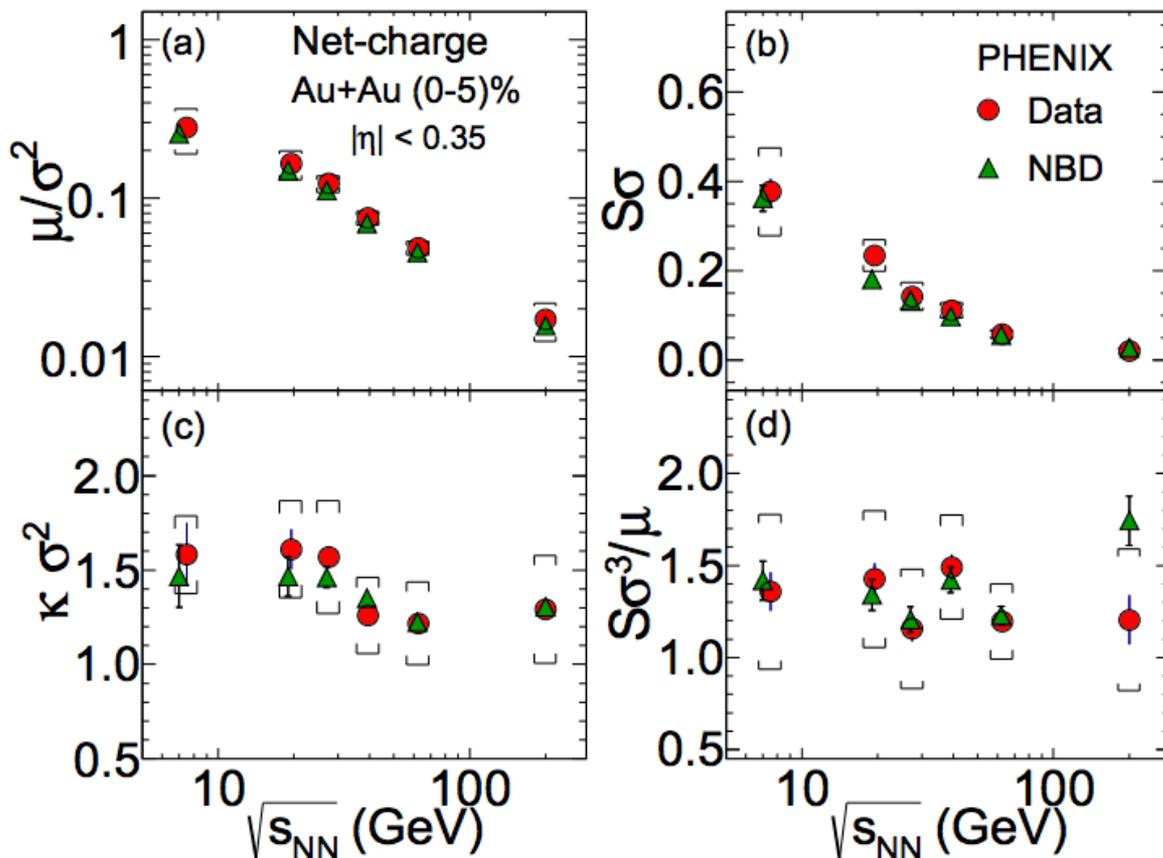
- σ^2/M increases with increasing energy, consistent with Poisson expectation.
- $S\sigma/Skellam$ increases with increasing energy.
- Non-monotonic behavior of net-proton $\kappa\sigma^2$ seen in 0-5% and 5-10% central collisions, the value of $\kappa\sigma^2$ go down below unity and then rise up from high to low collision energies.
- Peripheral collisions show smooth trend.
- UrQMD (no Critical Point), shows suppression at lower energies - due to baryon number conservation.

- STAR results on collision energy dependence of net-Proton, net-Kaon and net-Charge cumulant ratios for Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4$ and 200 GeV are presented.
- The values of net-Kaon's and net-Charge's $\kappa\sigma^2$ and $S\sigma/Skellam$ are consistent with Poisson distributions within errors.
- Non-monotonic behavior seen in net-Proton $\kappa\sigma^2$ in 0-5% and 5-10% central collisions.

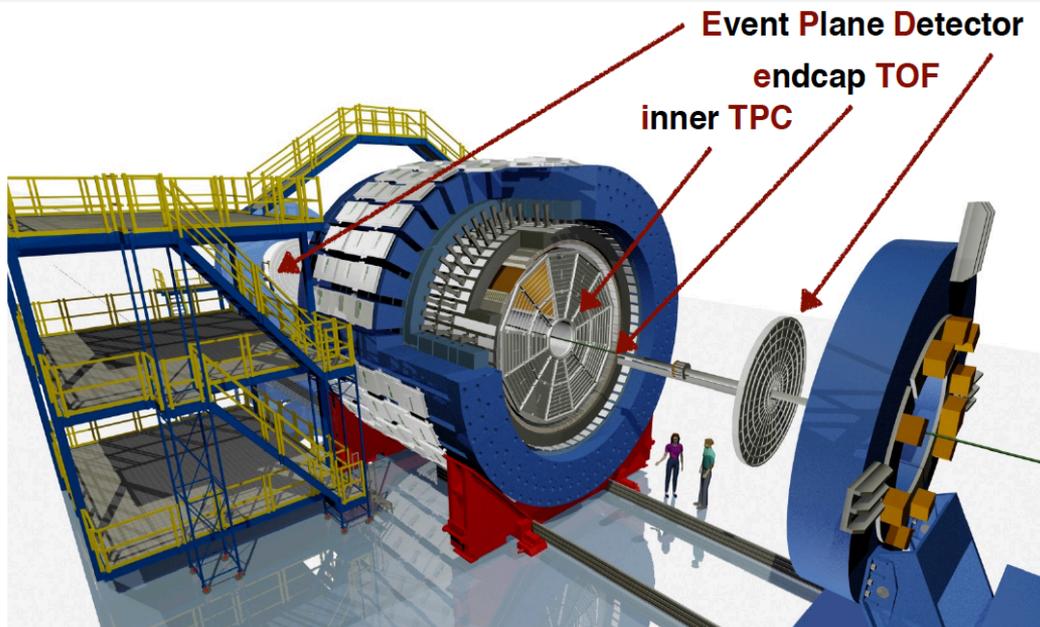
Back Up

A.Adare et al., Phys. Rev. C 93, 011901 (2016)

$|\eta| < 0.35, 0.2 < p_T < 2.0$ GeV/c



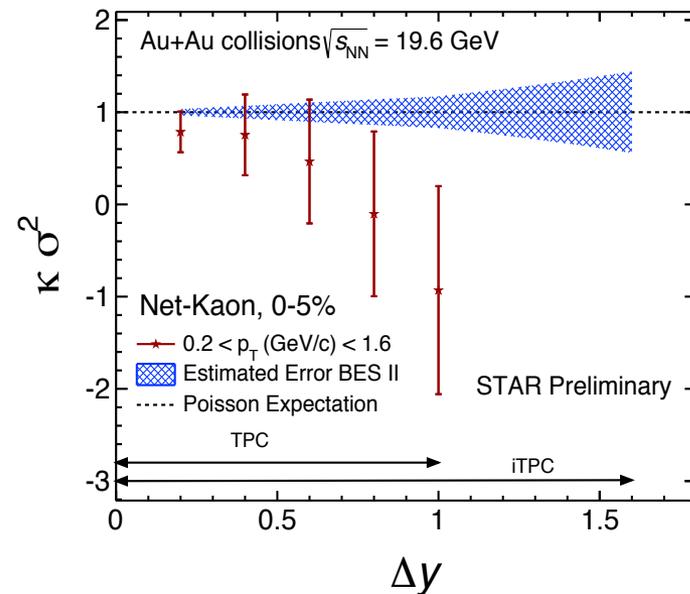
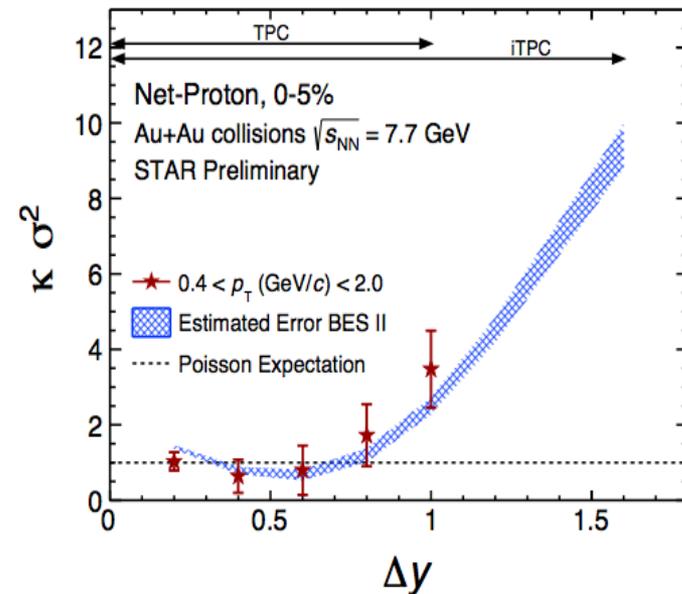
- Smaller error bars are due to small acceptance, both (η, ϕ) .
- “No clear evidence for structure attribute to the CP.”



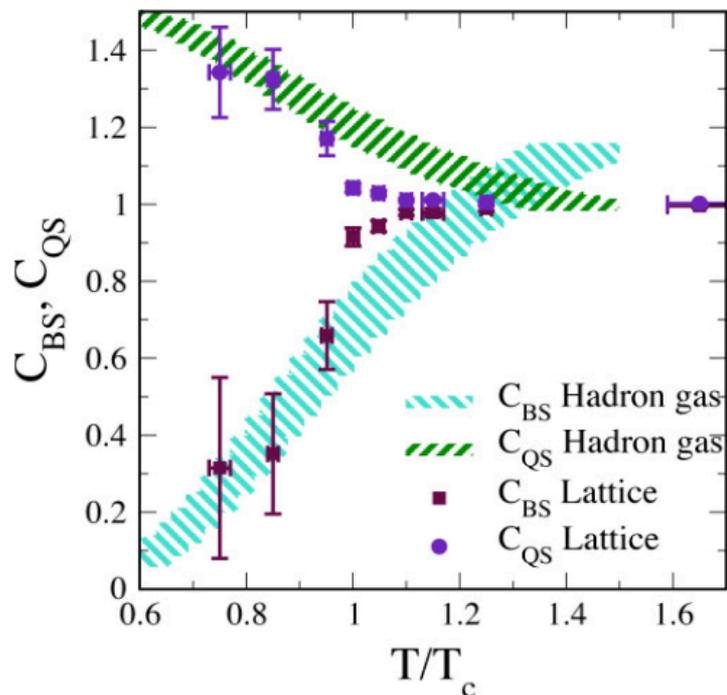
iTPC proposal: <http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619>
 BES-II whitepaper: <http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598>

Errors estimate from: X. Luo, PHys. Rev. C91, 034907 (2015)
 Δy trend from: Bo Ling, Misha Stephanov, arXiv: 1512.09125

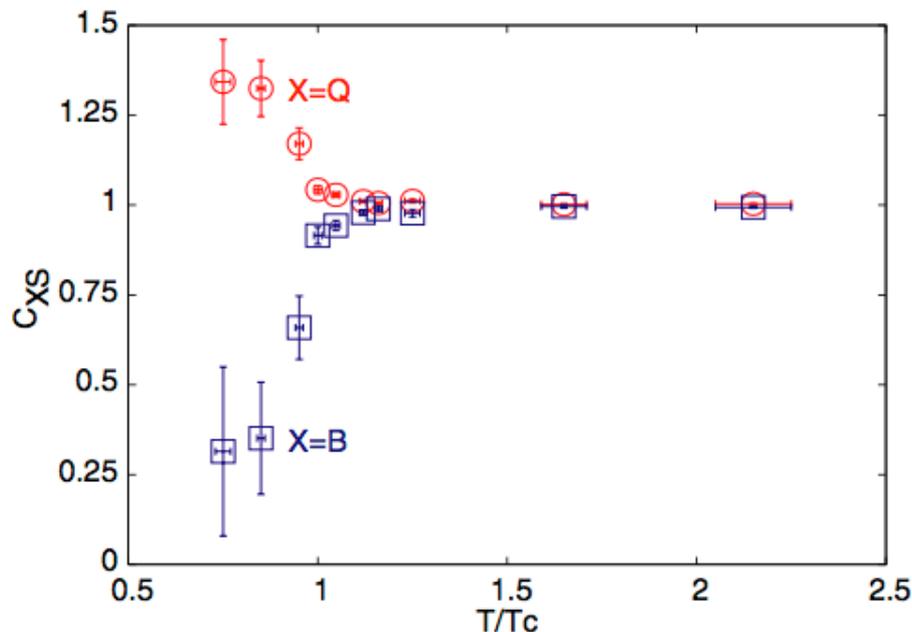
- Inner TPC(iTPC) upgrade : $|\eta| < 1$ to $|\eta| < 1.5$, better dE/dx resolution.
- Forward Event Plane Detector (EPD): Centrality and Event Plane Determination.
 $1.8 < |\eta| < 4.5$



A. Majumder and B. Muller, Phys. Rev. C 74 (2006)



R. V. Gavai and S. Gupta, Phys. Rev. D 73 (2006)



Correlation of charge and strangeness:

$$C_{QS} = 3 \frac{\chi_{QS}^2}{\chi_S^2}$$

$C_{QS} = 1$ for $T > T_C$
 $C_{QS} > 1$ for $T < T_C$

Correlation of baryon and strangeness:

$$C_{BS} = 3 \frac{\chi_{BS}^2}{\chi_S^2}$$

$C_{BS} = 1$ for $T > T_C$
 $C_{BS} > 1$ for $T < T_C$